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The Raman Contribution to the Intensity Dependent Refractive Index in Optical Fibers

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***Abstract*—We report on the Raman contribution to the intensity dependent refractive index in step-index fibers with germanium doped silica core. The f_R value is found to be 0.157 ± 0.07 for a field weighted germanium concentration between 5 and 25 $\mathrm{mol}\ \%$.**

Knowledge about the intensity dependent refractive index is important within the field of non-linear optics. Therefore, it is only natural that measurements of the intensity dependent refractive index have been given significant attention over the years [1]–[6]. However, only a few of the reported works have tried to take into account the Raman contribution to the intensity dependent refractive index [7]–[9]. The non-linearity of a given material is commonly modelled as a sum of an electronic response, a vibrational/rotational response, and an acoustic response. For silica the electronic response is in the order of a few fs, the vibrational/rotational response is in the order of a few hundreds of fs, and the acoustic response is of the of order of few ns [10]. When working within the regime of fs pulses the acoustic response is non existing [10] and the contribution to the non-linearity is therefore of electronic and vibrational/rotational origin. This is often modelled with a response function given as $R(t) = (1 - f_R)\,\delta(t) + f_R h_R(t)$, where $h_R(t)$ is the Raman response function, the delta function represents the instantaneous electronic response, and f_R is the ratio between the Raman contribution to the intensity dependent refractive index and the intensity dependent refractive index itself [11], [12]. For a pure silica core fiber f_R is reported to be 0.18 [7]. This value is often adopted also for pulse propagation in other silica based fibers. However, this is questionable as the different dopants influence this ratio. Here we focus on the ratio, f_R, as a function of different germanium concentrations. This is done by measuring the intensity dependent refractive index and corresponding Raman gain spectrum. From the Raman gain spectrum the contribution from the Raman effect to the intensity dependent refractive index is calculated, thus it is possible to obtain the f_R ratio.

The non-linearity of different fibers is measured with a self-phase modulation (SPM) based technique [3]. A sketch of the setup is seen in Fig. 1, the channel separation of the two PM CW DFB lasers is 0.2 nm. The non-linear fiber paramater is given as $\gamma = \frac{2\pi n_2^I}{\lambda A_{eff}}$, where n_2^I is the intensity dependent refractive index, λ is the wavelength, and A_{eff} is the effective area [12]. The contribution to the intensity

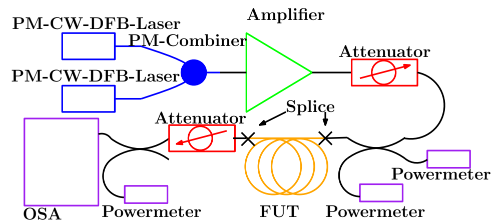

Fig. 1. Sketch of the SPM-based setup.

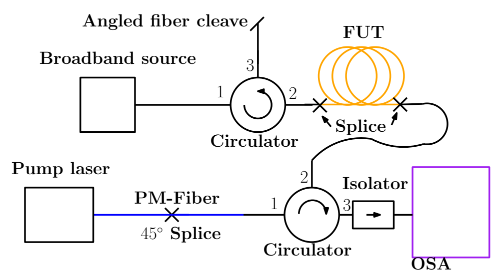

Fig. 2. Sketch of the setup for the Raman gain measurement.

dependent refractive index from the Raman effect is calculated following the method from [7] by applying the Kramers-Kronig relations to the measured Raman gain. The setup for measuring the Raman gain is seen in Fig. 2. If the Raman effect is written as a complex refractive index, denoted as $n_{2,R}^I + i\kappa_{2,R}^I$, where $n_{2,R}^I$ is the real part of the Raman complex refractive index, which contributes to the intensity dependent refractive index and $\kappa_{2,R}^I$ is the imaginary part, which is related to absorption and gain. The Raman gain coefficient is given as $g_R = -2\frac{2\pi}{\lambda}\frac{\kappa_{2,R}^I}{A_{eff,R}}$, where $A_{eff,R}$ is the effective Raman area, which takes the changing field overlap with wavelength into consideration [13]. The SPM-based measurement is done at wavelength of 1550 nm, whereas the Raman measurement is done with a pump laser at 1453 nm. It is assumed that the intensity dependent refractive index is independent of wavelength within the considered wavelength region [4]. The fibers used in this investigation consist of simple step-index fibers, which have germanium doped silica in the core and a cladding of pure silica. This is done to avoid other dopant materials such as fluorine and phosphor to the intensity dependent refractive index. The intensity dependent refractive index is plotted as a function of how much germanium the light interacts with, which is calculated as $C_{ge} = \frac{\int_0^\infty x_{ge}\left(|F|^2\right)^2 r\mathrm{d}r}{\int_0^\infty \left(|F|^2\right)^2 r\mathrm{d}r}$, where r is the radial coordinate, F is the transverse field distribution of the electric field, and x_{ge} is the molar germanium concentration at a given point. All of the values x_{ge}, A_{eff}, and $A_{eff,R}$ are calculated from the measured index profile of the fiber. The resulting intensity dependent refractive indices from the SPM-based and the Raman measurements are shown in Fig. 3 and in Fig. 4, respectively.

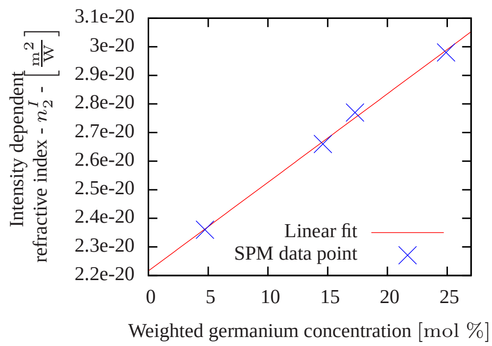

Fig. 3. The intensity dependent refractive index from both the electronic and vibrational/rotational contributions plotted as a function of how much germanium the light experiences.

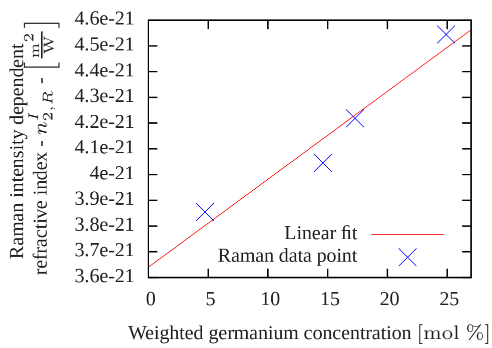

Fig. 4. The intensity dependent refractive index from the vibrational/rotational contributions plotted as a function of how much germanium the light experiences.

The ratio between the Raman contribution to the intensity dependent refractive index and the intensity dependent refractive index itself is calculated from Figs. 3 and 4 and shown in Fig. 5

The f_R for the measured fibers is seen to be within 0.163 to 0.152. The small variations of data points becomes greater in the calculation of the f_R value and the ratio of the data points seems to have a more step like behaviour, whereas the ratio of the two linear fits is smoothly degreasing. The ratio of the two linear fits is decreasing from 0.164 to 0.150 with increasing germanium light interaction, within the shown interval. In the case of a high interaction between the light and germanium the f_R value is 0.15 and hence, one would introduce an error of 20% in the f_R value, when using the commonly used f_R value

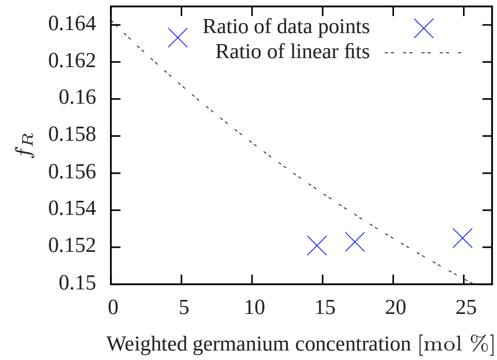

Fig. 5. The resulting f_R ratio from the values of Figs. 3 and 4. The f_R ratio is plotted as a function of how much germanium the light experiences.

of 0.18 reported for a pure silica fiber. This has a significant impact in any application where the Raman effect plays a key role as the f_R is directly proportional with the strength of the Raman gain and therefore also with the soliton self-frequency shift.

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